UNDERSTANDING THE PHYSIOLOGICAL, BIOMECHANICAL, AND PERFORMANCE EFFECTS OF BODY ARMOR USE

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ABSTRACT

This study was conducted to compare the effects on Soldiers' physiological, biomechanical, and maximal performance responses of not wearing any armor, wearing an armor vest, and wearing a vest plus extremity armor. Eleven Army enlisted men participated in the study. Participants carried out the following activities on separate days of testing: walking (1.39 m/s); running (2.34 m/s); and three maximal effort tasks. The maximal effort tasks were: five continuous 30-m rushes; 5 min of repetitive lifting of a 20.5-kg box; and obstacle course runs. The walking and the running trials were 10 min in duration and took place on a level treadmill. Each participant was tested in five conditions: no armor, the Interceptor Body Armor tactical vest, and three types of extremity armor, which were worn with the armor vest. The vest was configured with a collar, groin protector, and protective inserts. The three designs of extremity armor were similar in weight, but varied in body surface area covered. The results indicated that mean $\dot{V}O_2$ scaled to body mass was significantly higher during walking when extremity armor was worn than when armor was not used or only the armor vest was worn. The kinematic and kinetic data revealed significant changes in walking and running biomechanics when extremity armor was worn compared to not wearing armor. With the extremity armor, volunteers walked and ran with wider strides, increased stance time, and decreased swing time. They also braked with higher ground reaction forces at heel strike and pushed off with higher forces at toe off when extremity armor was worn. In addition, performance on maximal effort tests was poorer when extremity armor was worn than when armor was not used or only the armor vest was worn. This study demonstrated that use of extremity armor increases users' metabolic cost while performing Soldier tasks and alters gait biomechanics compared to no armor or an armor vest alone.

1. INTRODUCTION

The current battlefields require a highly mobile, rapidly deployable ground force that will face increasingly sophisticated weaponry in diverse environments. The lethality of these environments requires members of the armed forces to wear protective gear that provides a balance between protection and functionality. Soldiers and Marines deployed to Iraq and Afghanistan wear the Interceptor Body Armor (IBA) tactical vest with groin protector to protect against shrapnel and hand gun rounds. Small Arms Protective Inserts are added to protect against rifle ammunition. The IBA is an effective and highly valued piece of equipment and has saved many lives. Injury statistics compiled by the office of the U.S. Army Surgeon General indicate that just 7% of wounds sustained over a 14-month period during Operation Iraqi Freedom were to the torso area (COL Chuck Scoville, USA (Ret), personal communication, May 2004). The benefits of wearing the IBA appear to outweigh the limitations imposed because of increased loads, restricted mobility, and thermoregulation issues (Ricciardi, 2005).

From the time of the Korean War, when body armor for ground troops was first introduced, up to the present, great improvements have been made in the ballistic protection afforded to Soldiers and Marines in the face of evolving types of munitions, and this has been achieved while reducing armor weight and increasing compatibility of the armor with the mission-related tasks that dismounted troops must carry out. What has remained essentially unchanged in the armor used over these years is the portion of the body covered by ballistic protective materials. However, because of the battlefield threats being encountered by Soldiers and Marines serving in Operation Enduring Freedom and Operation Iraqi Freedom (OEF/OIF), the Army and the Marine Corps have launched initiatives to increase the body area coverage to include the arms and the legs.

1.1 Effects of Armor Vests on Performance

Research into the effects of body armor on aspects of performance germane to tactical operations of military ground troops is not extensive. Most of the studies that have been done involved some form or variation of an armor vest, but not armor to protect the extremities.

Thermal stress imposed by vest wear has been the focus of a number of investigations (Cadarette, Blanchard, Staab, Kolka, & Sawka, 2001; Haisman & Goldman, 1974). The temporal and kinematic characteristics of a dynamic, repetitive motion have also been examined for armor vest effects. Martin and Nelson (1982, 1986) captured and analyzed the movements of men and women walking on a level surface at a velocity of 1.78 m/s while dressed in a number of outfits that

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varied in the items worn and in weight. A minimal clothing/minimal weight condition consisted of a T-shirt, shorts, and sneakers (~0.7 kg). A second condition consisted of a field uniform, combat boots, and a fighting load (~9.2 kg). A helmet and an armor vest were added to obtain a third condition (~17.0 kg). Analyses of stride variables revealed that stride length, single leg contact time, and double support time when the armor was used did not differ significantly from the minimal clothing condition. However, stride rate (in strides/s) was significantly higher and swing time was significantly shorter for the armor vest than for the other two conditions. Martin and Nelson ascribed the differences in gait to the variations in the magnitudes of the external load on the body.

1.2 Energy Cost of Carrying External Loads on the Torso

Research has been completed on the effects of carrying backpack loads on the rate of oxygen uptake ($\dot{V}O_2$), an index of energy cost (Knapik, Harman, & Reynolds, 1996). In studies done on marching with backpack loads, it has been found that energy cost increases with increases in the mass of the load and the speed of walking (Pandolf, Givoni, & Goldman, 1977; Polcyn et al., 2002; Soule, Pandolf, & Goldman, 1978).

Very little research has been done on the energy cost of walking with and without body armor, and that research has involved armor vests, but not extremity armor. Legg and Mahanty (1985) investigated various means of carrying a load on the torso. They found that the energy cost of walking in a vest loaded to 35% of body weight was approximately equal to the energy cost of walking with a backpack loaded to the same weight. Both approaches for carrying the load increased $\dot{V}O_2$ relative to an unloaded condition by about 30 to 35%.

1.3 Effects of Loads Added to the Extremities

The research done to quantify the effects of body armor on performance is limited, and armor vests, not ballistic protective items for the extremities, have been the focus of the work that has been undertaken. However, some information on the possible effects of extremity armor on performance may be gleaned from studies in which loads have been placed on the upper and the lower extremities.

1.3.1 Upper Extremity Weighting

The effects of load added to the upper extremities on oxygen uptake during walking and running have been researched and it has been shown that adding weight to the upper extremities is not as efficient in terms of energy usage as adding weight to the torso. Soule and Goldman (1969) found that the energy cost of walking with a given mass on the hands is about 1.4 to 1.9 times greater than the cost of the same mass on the torso. Miller and Stamford (1987) reported a 13% increase in energy expenditure per 1.0 kg of added weight. The location of weighting the upper extremity at the hands as compared to the wrist also demonstrated a physiologic difference in energy cost.

1.3.2 Lower Extremity Weighting

A number of investigators have reported that the energy cost of walking with a given mass on the feet is 4 to 6 times greater than the cost of the same mass on the torso (Catlin & Dressendorfer, 1979; Holewijn, Heus, & Wammes, 1992; Jones, Knapik, Daniels, & Toner, 1986; Jones, Toner, Daniels, & Knapik, 1984; Legg & Mahanty, 1986; Soule & Goldman, 1969). Research results also indicate that increases in footwear weight substantially increase the energy cost of walking. The findings are in general agreement that there is a 5 to 10% increase in energy expenditure per 1.0 kg of added weight to the feet (Catlin & Dressendorfer; Jones et al., 1986; Legg & Mahanty; Martin, 1985; Miller & Stamford, 1987). Loading the lower extremities during running has similar physiological effects to those associated with walking (Claremont & Hall, 1988; Martin, 1985).

1.4 Purpose of Study

The purpose of the study was to compare the effects on Soldiers' physiological, biomechanical, and maximal performance responses of not wearing any armor, wearing an armor vest, and wearing a vest plus extremity armor. Three types of extremity armor were tested, each of which was designed to provide ballistic protection to the arms and the legs. Physiological and biomechanical data were collected during walking and running. Physical activities, consisting of box lifting and carrying, 30-m rushes, and obstacle course runs, were used to measure maximal effort performance.

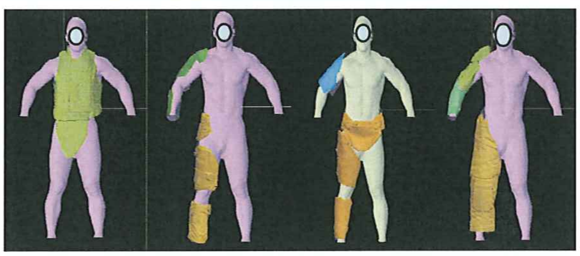
2. METHODS

Participants were 11 U.S. Army enlisted men (means—age: 20 years; height: 1.8 m; weight: 79.7 kg) recruited from among the military personnel who serve as human research volunteers assigned to Headquarters Research and Development Detachment, U.S. Army Soldier Systems Center, Natick, MA. Ten of the men (MOS 11B, infantry) had just completed Infantry Advanced Individual Training (mean time in service: 5 months). One man (MOS 19K, armor crewman) had time in service of 20 months. Informed consent was obtained and the study was conducted in accordance with Army Regulation 70-25. All volunteers were healthy and without musculoskeletal injuries or disorders.

Each participant was tested in five conditions: no armor (NA); the Interceptor Body Armor tactical vest, including collar, groin protector, and protective inserts (VEST); and the three types of extremity armor (EXT 1, 2, 3), which were worn with the vest. The three designs of extremity armor were similar in weight, but varied in body surface area covered (Table 1). Three-dimensional scans of the body surface were made in the armor conditions under study and surface area covered by armor was calculated. The scans in Figure 1 illustrate differences in coverage among the three designs and area coverage provided by the armor vest.

Table 1. Mean Armor Mass and Coverage Area

	VEST	EXT 1	EXT 2	EXT 3
Weight (kg)	8.7	5.6	6.4	5.6
Coverage (m^2)	.411	.717	.775	.926



VEST EXT 1 EXT 2 EXT 3

Figure 1. Examples of 3-dimensional laser scans of armor vest coverage and extremity armor coverage of the right side of the body.

2.1 Testing Equipment

For testing during treadmill walking and running, a force plate treadmill, fabricated by AMTI (Watertown, MA), was used. This treadmill is comprised of two synchronized treadmills on a single platform and is capable of measuring ground reaction force in three planes. Each force plate in the treadmill provides six continuous voltage output signals corresponding to forces and torques in three orthogonal directions (x, y, z). The voltages at each input channel were converted at the rate of 1200 Hz to digital values and stored in computer data files. The kinetic data were used to assess effects of the armor conditions on ground reaction force-time histories. A number of variables were derived from these data, including peak vertical, braking, and propulsive forces. For analysis, the forces were indexed to the volunteer's body mass (N/kg).

Three-dimensional motion was recorded by ProReflex Motion Capture Unit (MCU) cameras (Qualisys Medical AB, Gothenburg, Sweden) as the volunteers walked or ran on the treadmill. These data were used to analyze gait kinematics. Retro-reflective markers, about 12 mm in diameter, were placed at selected locations on the volunteer's skin and clothing to expedite processing of the gait kinematics. To capture the volunteer's movements on the treadmill, eight MCU cameras, operating at 120 Hz, were focused on the area of the treadmill. The cameras were positioned on each side and anterior and posterior to the viewing area. This allowed the kinematics of the whole body to be defined in three-dimensional space with 6 degree of freedom biomechanical movement analysis for each body segment. The outputs of the cameras and the force plates were collected through a single data acquisition (DAQ) system and were time-synchronized.

The recorded images were processed using dedicated hardware and software (Qualisys Medical AB, Gothenburg, Sweden) to produce files containing time histories of the three-dimensional coordinates of each reflective marker. The Visual 3-D software program (C-motion Inc., Rockport, MD) was used to process the data files to produce histories of numerous kinematic variables describing the volunteer's posture and gait. The kinematic data were analyzed to determine the extent to which gait parameters and body posture were affected by the test conditions.

Oxygen uptake was measured in the study using the COSMED $K4b^2$ metabolic analysis apparatus (Rome, Italy). The apparatus includes a portable unit that contains the O_2 and CO_2 analyzers, sampling pump, UHF transmitter, barometric sensors and electronics. The rate of oxygen consumption, as recorded with the $K4b^2$ unit, was expressed in absolute terms (L/min). For analysis purposes, it was scaled to the volunteer's body mass (ml/kg/min).

2.2 Testing Procedures

2.2.1 Biomechanical and Metabolic Analysis of Treadmill Walking and Running

For walking trials, the force plate treadmill was set at a speed of 1.34 m/s and a 0% grade. For running, treadmill speed was 2.24 m/s and the grade was again 0%. Prior to the days of formal testing, volunteers were familiarized with walking and running on the force plate treadmill at these speeds. For familiarization, a volunteer first walked at 1.34 m/s without any body armor. Then, the speed was gradually increased and the volunteer ran at 2.24 m/s. Familiarization continued with the volunteer walking and then running at these same speeds for 10-min periods wearing the armor vest alone and with each type of extremity armor. On days of formal testing, a volunteer had four, 10-min trials of walking or four, 10-min trials of running. The volunteer walked or ran continuously throughout the 10-min period. A different armor condition was tested on each of the four trials. There was a 15-min rest period between trials. Within a running or a walking trial, force plate and camera outputs were recorded for 2 min after the trial had been underway for 5 min. Ten strides, five initiated with a right heel strike and five with a left heel strike, were selected for subsequent analysis from the recorded ground reaction force data and motion data. At approximately 7 min into the trial, oxygen uptake was measured for 90 s.

2.2.2 Repetitive Box Lift and Carry

This activity entails lifting a metal box by its handles and carrying it. The box is approximately 38 cm wide, 11 cm deep, and 23 cm high. There are opposing handles on two sides of the box. For this study, the box was weighted to 20.5 kg. The box is initially positioned at floor level, 3.05 m away from and directly in front of a wooden platform. The height of the platform from the floor is 1.55 m (simulating the height of the bed of the newest Army 5-ton truck). The activity requires that an individual lift the box from the floor, walk to the platform, place the box on the platform, and return to the starting position for another box. A trial on this activity consisted of lifting and carrying the box as many times as possible within a 5-min period. The number of boxes lifted each minute and the total number lifted over 5 min were recorded. A volunteer performed this test once under each armor condition. The volunteer had no more than two trials per day, with a rest period of 20 min between the trials. Prior to the first day of testing, volunteers were given practice on this activity in order to learn how to execute it safely and to become familiar with performing the activity continuously for 5 min.

2.2.3 30-m Rushes

Two, padded gym mats were placed on the floor approximately 30 m apart. This activity started with a volunteer in a prone position on one mat facing the opposing mat. Upon an auditory signal from an investigator, the volunteer got up and ran forward, assumed a prone position on the opposing mat 30 m away, and turned to face the direction of the starting position. Five seconds later there was another auditory signal, upon which the volunteer proceeded in the same manner back to the starting position. This cycle was repeated until five, 30-m rushes were completed. For scoring, the time to complete each individual rush and the total time to complete the five rushes were recorded. Volunteers participated in one trial (i.e., five rushes) under each armor condition. They were encouraged to complete each rush as quickly as possible. On any one day of testing, a volunteer participated in no more than two trials on this activity with a rest break of 10 min between the trials. On a day preceding testing, volunteers were familiarized with this activity by performing two to three rushes as quickly as possible.

2.2.4 Obstacle Course Runs

The obstacle course includes: a set of four plastic hurdles, 0.6 m high; a field of 9 rubber cones delineating a zigzag running pattern, 27 m long and 1.5 m wide; a crawl space of wood/wire, 0.6 m high, 0.9 m wide, and 3.7 m long; a horizontal shimmy pipe, 3.7 m long; a 1.4-m high sheer wooden wall without footholds or ropes; a 27-m straight run; a jump and reach activity; and stair climbing. Total course completion time and times to complete each obstacle or course segment were recorded using electronic timing devices (Brower Timing Devices, Salt Lake City, UT) placed along the course. The score was the total time to complete one run of the entire course. A volunteer completed one run of the course under each armor condition. The volunteer had no more than two course runs on a single day, and there was a 20-min rest period between the runs.

2.2.5 3-Dimensional Body Scanning

A Cyberware WB4 whole-body 3D surface scanner (Cyberware, Inc., Monterey, CA) was used to capture body surface data for extremity armor coverage analysis. The WB4 utilizes low-powered planes of visible (red) and infrared laser light to illuminate a horizontal stripe around the body that is then digitized with standard digital cameras. Luminance or RGB color texture maps are captured during scanning, as well. To determine extremity armor coverage, the cross-section method was used, as described in Figures 2 and 3.

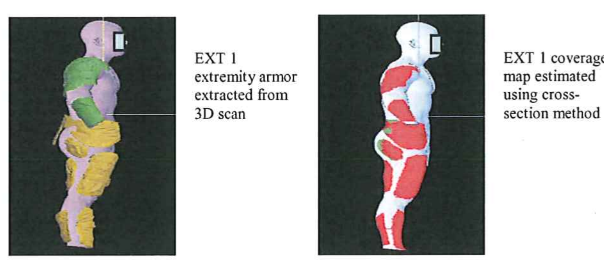


Figure 2. 3D scan and coverage map for EXT 1.

2.3 Data Processing and Statistical Analysis

To address the objective of investigating the effects of body armor on performance, a one-way repeated measures analysis of variance (ANOVA), with five levels of the armor variable (NA, VEST, EXT 1, EXT 2, EXT 3), was carried out on each of the quantitative dependent measures recorded in this study. All statistical analyses were accomplished using SPSS 13.0. An effect was statistically significant if the likelihood of its occurrence by chance was $p < .05$. In those instances in which an ANOVA yielded a significant main effect of armor, post-hoc analyses in the form of the Least Significant Difference procedure were performed, with the significance level again set at $p < .05$.

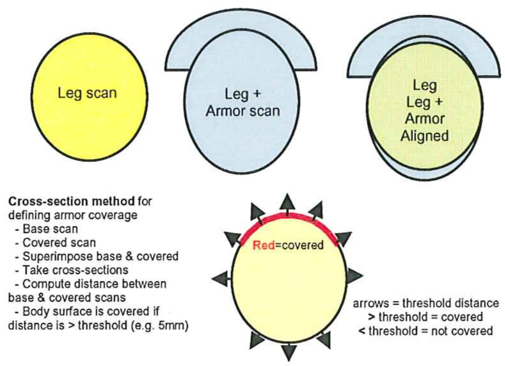


Figure 3. Cross-section method for defining armor coverage.

3. RESULTS

In the analyses of $\dot{V}O_2$ for walking and running, values for the no-armor condition and the vest were similar and values for the three types of extremity armor did not differ significantly from each other. However, $\dot{V}O_2$ was about 17% and 7% higher during walking and running, respectively, with the extremity armor than without armor or with the armor vest only (Figure 4).

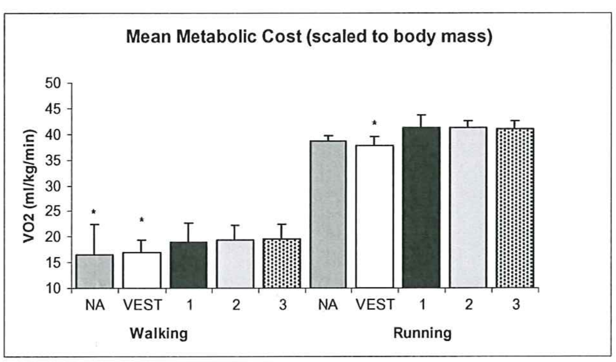


Figure 4. Means for each armor condition of $\dot{V}O_2$ scaled to body mass. (*) indicates significant difference ($p < .05$). Error bars indicate +1 SD.

Analyses of the kinematic data for walking revealed that, compared with no armor, there were significant increases in double-support time when armor was worn. Stance time was significantly longer and swing time significantly shorter with EXT 3 than with any of the other conditions. Stride width was significantly greater with EXT 2 and 3 than with no armor. The kinetic data analyses yielded vertical ground reaction forces at heel strike and toe off during walking that were significantly higher with the vest compared to no armor and increased significantly again with the extremity armor. Additionally, braking and propulsive forces increased with the addition of the vest and extremity armor to the body (Table 2).

Table 2. Means (SD) for Walking Biomechanics

Walk Variable	NA	VEST	EXT 1	EXT 2	EXT 3
Double Supp. Time (% Stride)	30.541_A (1.186)	31.753_B (1.550)	32.745_B (1.528)	32.588_B (1.359)	32.526_B (1.580)
Stance Time (s)	0.713_A (0.025)	0.727_{AB} (0.024)	0.723_{AB} (0.030)	0.726_{AB} (0.031)	0.712_B (0.032)
Stride Width (m)	0.147_A (0.018)	0.148_{AB} (0.018)	0.157_{AB} (0.027)	0.167_B (0.023)	0.162_B (0.024)
Swing Time (s)	0.380_A (0.016)	0.376_{AB} (0.017)	0.366_{AB} (0.016)	0.369_{AB} (0.014)	0.363_B (0.020)
Braking (N/kg)	-1.864_A (0.195)	-2.144_B (0.254)	-2.297_{BC} (0.353)	-2.401_C (0.378)	-2.253_{BC} (0.307)
Propulsion (N/kg)	1.900_A (0.216)	2.209_B (0.144)	2.413_C (0.195)	2.445_C (0.174)	2.394_C (0.150)
Heel Strike (N/kg)	11.384_A (0.434)	12.541_B (0.539)	13.455_C (0.775)	13.376_C (0.663)	13.091_C (0.535)
Toe Off (N/kg)	11.484_A (0.657)	12.593_B (0.669)	13.480_C (0.861)	13.508_C (1.008)	13.460_C (0.804)
Means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$)					

Analyses of running kinematics revealed that stance times were significantly longer with EXT 1 and 3 than with the no armor condition. Swing time was significantly shorter with the armor vest and the extremity armor than without armor. The kinetic results for vertical force at heel strike were similar to those obtained for walking insofar as the lowest force was associated with no armor. As with walking, the braking force increased with the addition of the vest and extremity armor (Table 3).

Table 3. Means (SD) for Running Biomechanics

Run Variable	NA	VEST	EXT 1	EXT 2	EXT 3
Stance Time (s)	0.335_A (0.014)	0.347_{AB} (0.016)	0.347_B (0.016)	0.349_{AB} (0.015)	0.345_B (0.014)
Swing Time (s)	0.432_A (0.034)	0.399_B (0.025)	0.400_B (0.024)	0.395_B (0.026)	0.396_B (0.020)
Stride Width (m)	0.099_A (0.017)	0.095_A (0.015)	0.116_B (0.015)	0.111_{AB} (0.015)	0.117_B (0.018)
Braking (N/kg)	-2.161_A (0.308)	-2.442_B (0.224)	-2.73_C (0.299)	-2.646_{BC} (0.253)	-2.510_B (0.330)
Propulsion (N/kg)	1.621_{AB} (0.184)	1.588_A (0.307)	1.789_B (0.372)	1.637_{AB} (0.355)	1.691_{AB} (0.300)
Heel Strike (N/kg)	22.347_A (1.659)	23.416_{AB} (2.276)	24.872_B (2.570)	24.054_B (2.489)	24.780_B (2.623)
Means that do not share the same subscript differed significantly in post-hoc tests ($p < .05$)					

On the maximal performance tests, scores were poorer with the armor vest than without any armor (Figure 5). In addition, a consistent finding on the three performance tests was that the poorest scores were achieved with EXT 3.

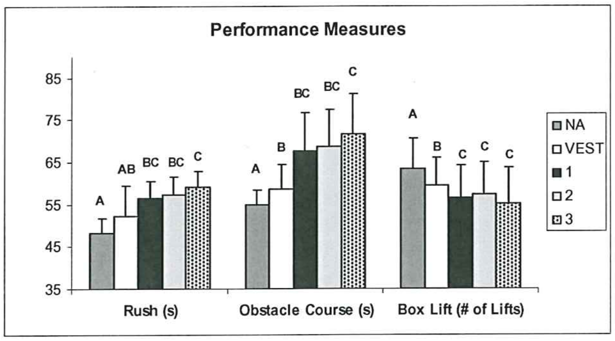


Figure 5. Means for each armor condition on the performance measures. Means that do not share the same letter differed significantly ($p < .05$). Error bars indicate +1 SD.

4. DISCUSSION

The three types of extremity armor used in this study were approximately equal in weight, differing by less than 1 kg. They did, however, differ substantially in the total surface area of the body covered by ballistic materials. EXT 3 was highest by far in area coverage. This more extensive coverage of the body did not prevent users of EXT 3 from carrying out any of the study-related physical activities. However, considering the overall results from this study, performance with EXT 3 differed from that with the armor vest alone to a somewhat greater extent than performance with the other two extremity armor systems did. The extremity armor system with the least area coverage was EXT 1. In terms of overall performance on the tests included in the study, results with EXT 1 were somewhat better than those with EXT 3 and similar to those with EXT 2.

The extremity armor added considerably to the load that study volunteers were bearing on their bodies. The mass of the clothing worn plus the mass of the armor vest, including plates, totaled 19% of the volunteers' average body mass. When the extremity armor was used, the mass of all the items worn or carried by the volunteers was increased to about 26% of average body mass. Findings from past research on load carrying support the postulation that extremity armor weight had a negative influence on execution of the physically demanding maximal performance tests used in this study. Investigations comparing completion times on obstacle course runs and other maximal performance tests with and without backpack loads found that times increased substantially when a load was carried (Harman et al., 1999). Also, in reporting on effects of increasingly heavy loads, Polcyn et al. (2002) provided data indicating that completion times on maximal performance tests increase in a linear fashion with load mass increases.

Energy cost data from the 10-min periods of walking at 1.34 m/s and running at 2.24 m/s provide some insight into the manner in which armor weight influenced the volunteers' basic physiological processes. The measure of energy cost used in this study was the rate of oxygen uptake. After adjusting oxygen uptake for the volunteers' body mass, the energy costs of walking and running were found to be significantly lower with the armor vest alone than when any of the three types of extremity armor were also worn. Compared with the vest, oxygen consumed per unit body mass was 22 to 26% higher during walking and 7% higher during running in extremity armor.

Energy cost is a critical consideration in assessing differences among the armor configurations tested here because higher energy costs of executing physical activities have negative implications for military operations. During prolonged bouts of walking and running under field conditions, for example, with higher energy consumption there is an increased probability that personnel will slow their pace or take more frequent rests. Efficiency in executing physically demanding tactics may also decrease because of the greater exertion required. In the study, the speed and duration of the bouts of walking and running were imposed by the investigators and, thus, the volunteers could not lower their activity levels to lower their exertion. In a military field situation, however, personnel might well lower their activity levels, if circumstances permit, in order to sustain prolonged exercise and minimize fatigue.

Like the analysis of energy cost, the analyses of the biomechanical data provide information regarding the influence of armor weight during walking and running. The measures of ground reaction force were normalized to the volunteers' body mass and then analyzed. From analyses of the vertical component during walking, it was found that the forces at heel-strike and at toe-off were significantly lower in magnitude with the no-armor and the armor vest conditions than with any of the types of extremity armor. The addition of the extremity armor increased the forces by about 6% relative to the forces with the armor vest alone. The running data were analyzed for vertical force at heel strike and values for the no-armor condition were found to be significantly lower than those for the three extremity armor conditions. The forces for the extremity armor were approximately 8 to 11% greater than the magnitude of the force for the no-armor condition. With the vest alone, vertical force at heel strike during running was 5% greater than the force for the no-armor condition.

Even when only minimal clothing is being worn, vertical ground reaction forces associated with locomotion can be very high. In this study, the vertical forces during walking in the vest alone were 30% greater than the volunteers' mean body weight and, during running in the vest, they were about 2.3 times mean body weight. These findings are in consonance with reports from investigations in which gait kinetics were examined for effects of varying the masses of load-bearing equipment (Harman et al., 1999; Polcyn et al., 2002). Repeated exposures of the body to the high vertical forces that occur every time the foot contacts and subsequently pushes off from the ground during walking and running have been postulated to contribute to the onset of acute and chronic injuries, particularly overuse injuries of the lower extremities (Knapik et al., 1996). A possible consequence of increasing already high vertical forces by adding extremity armor or other items that increase the external load on the body is to increase the probability of incurring such injuries.

The results for the oxygen uptake and the ground reaction force variables recorded during walking and running that have been considered up to this point in the discussion were obtained from analyses of the raw data adjusted to account for the volunteers' body mass. Additional analyses were carried out on the oxygen uptake and the ground reaction force variables using data adjusted to total mass, including body mass and the mass of the extremity armor, the vest, and of all other items being worn. Analyses of these data did not yield significantly higher energy costs or higher magnitude vertical forces with the extremity armor than with the armor vest alone.

Taken together with the data adjusted for the volunteers' body mass, the findings from the analyses of data adjusted for total mass confirm that there was a weight penalty associated with wear of the extremity armor. In addition, they indicate that other aspects of the extremity armor, such as design characteristics, did not also contribute to the increased energy cost and forces on the body during walking and running. However, there were measures taken in the study that did appear to be affected by differences in design among the three types of extremity armor. For example, performance on each of the three maximal effort tests was poorer with EXT 3 than with the other two types of extremity armor. With EXT 3, ballistic material covered a substantially greater portion of the surface area of the body than it did with EXT 1 and EXT 2. It is possible that movements of the lower extremities were encumbered with EXT 3 to the extent that running during the 30-m rushes, completing obstacles, and box lifting and carrying were slowed.

Analyses of gait kinematics for treadmill walking also suggest an encumbrance of lower extremity movements with EXT 3. Stance time was longer and swing time was shorter with EXT 3 than with the other two types of extremity armor, although the differences among extremity armor conditions did not achieve statistical significance on these two variables.

Another of the gait variables, stride width, would be expected to be affected by thickness of material in the crotch or the thigh areas. In analysis of the treadmill walking data, the differences among the types of extremity armor were not statistically significant. The treadmill running data yielded similar findings for the stride width variable.

The ideal extremity armor is, undoubtedly, a system that provides complete ballistic protection of the upper and lower extremities, weighs no more than a combat uniform, and does not impair performance of combat tasks to a greater extent than the combat uniform. Until the ideal is realized, use of extremity armor to gain ballistic protection will entail the addition of weight to the body and degradation in some aspects of performance. The increased energy cost of walking and running and the higher vertical ground reaction forces at heel strike and toe off during locomotion with the extremity armor tested here compared with the armor vest alone are illustrative of the weight-related trade-offs involved with increasing the ballistic coverage of the body.

5. CONCLUSIONS

Study results demonstrated that armor use changed gait patterns during walking and running compared to the no-armor condition. Armor vest weight increased forces on the body; forces increased further with the added weight of extremity armor. The implications are an earlier onset of muscle fatigue and increased risk for musculoskeletal injury when Soldiers wear armor. Not only the weight itself, but its location affected the user, as evidenced by the finding that armor on the arms and legs increased the energy cost of walking and running considerably compared with a condition in which armor was not worn, whereas the vest alone did not. Execution of maximal performance tests was impaired by the vest and, to a much greater extent, by the extremity armor. The added weight and encumbrance of the extremity armor likely played a role. The worst performance occurred with the extremity armor providing the greatest body area coverage, the only one of the three types with ballistic material covering the elbow and knee joints. Future biotechnology advancements in body armor will likely contribute as disruptive technologies to increase Warfighter protection without compromising endurance and mobility. Until then, developers of extremity armor will be faced with the trade-offs in user agility and mobility entailed in protecting entire limbs versus selectively placing ballistic materials to protect against the most traumatic injuries.

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